WHITE PAPER

GaN BDS TECHNOLOGY

Enphase Adoption of GaN Bi-Directional Switch Technology for Distributed Power Electronics

Safe harbor

Use of Forward-Looking Statements

This whitepaper contains forward-looking statements made pursuant to the Safe Harbor provisions of the Private Securities Litigation Reform Act of 1995, including, but not limited to, Enphase Energy's business strategies, including anticipated trends and developments in markets in which it operates and in the markets in which it plans to expand; the expected capabilities, features, performance, efficiency, reliability, availability, and cost advantages of GaN HEMT UDS and GaN HEMT BDS technology in Enphase current and future products; the expected conformance of HEMT BDS devices to existing industry standards, the expected timing, capabilities, and adoption of IQ9 and IQ10 generation Microinverters and the IQ Solid-State Transformer (IQ SST); the suitability of GaN BDS technology for commercial and industrial PV, battery storage, EV charging, and AI data center applications; expectations regarding the development of higher-voltage GaN BDS and GaN UDS devices including 900V and 1.2kV variants; expectations regarding the scalability of Enphase's manufacturing platform and supply chain; the expectation of semiconductor manufacturers developing GaN UDS and BDS devices and Enphase Energy's views on the size and growth of addressable markets for GaN-based power conversion products. Words used such as "anticipates," "believes," "could," "potential," "predicts," "continues," "designed," "estimates," "expects," "goal," "intends," "likely," "may," "ongoing," "plans," "projects," "pursuing," "seeks," "should," "will," "would" and similar expressions are intended to identify forward-looking statements, although not all forward-looking statements contain these words. All forward-looking statements are based on Enphase Energy's current assumptions, expectations and beliefs, and involve substantial risks and uncertainties that may cause results, performance or achievement to materially differ from those expressed or implied by these forward-looking statements. You are cautioned that these forward-looking statements are only predictions and may differ materially from actual future events or results. Such risks include, but are not limited to, technological development and validation risks; semiconductor supply availability and qualification timing; customer acceptance and adoption of new power semiconductor architectures; competitive dynamics; supply chain availability and costs; regulatory and interconnection requirements; execution risks related to new market entry; and other factors discussed in Enphase Energy's filings with the Securities and Exchange Commission, including those risks described in more detail in Enphase Energy's most recently filed Annual Report on Form 10-K and other filings made from time to time with the Securities and Exchange Commission. All forward-looking statements in this whitepaper are based on information currently available to Enphase Energy, and Enphase Energy assumes no obligation to update these forward-looking statements in light of new information or future events.

Industry Information

Information regarding market and industry statistics in this whitepaper is based on information available to Enphase Energy that it believes is accurate. Such information is generally based on publications that are not produced for purposes of economic analysis.

AUTHORS

Michael Harrison *Senior Power Electronics Architect*

Ravi Kapre *Senior Director, Semiconductor Technology*

Enphase Energy, USA · May 2026

ABSTRACT

Enphase Adoption of GaN Bi-Directional Switch Technology for Distributed Power Electronics

Announcements regarding the adoption of Wide Band Gap (WBG) semiconductor devices are becoming increasingly common across the power electronics industry. Silicon Carbide (SiC) Metal Oxide Semiconductor Field Effect Transistor (MOSFET) devices have already become the standard for most electric vehicle (EV) motor drives and are rapidly penetrating the latest generation of onboard EV chargers. Similarly, Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs) have achieved mainstream consumer recognition, driven by their widespread success in compact smartphone and laptop chargers.

Enphase Energy's adoption of GaN in its latest generation IQ9 Microinverters represents an important advancement in the commercialization of GaN bidirectional switch technology. This whitepaper explores the revolutionary device technology behind the GaN Bi-Directional Switch (BDS) - a breakthrough architecture that Enphase has helped advance and commercialize in collaboration with semiconductor partners.

01 Background

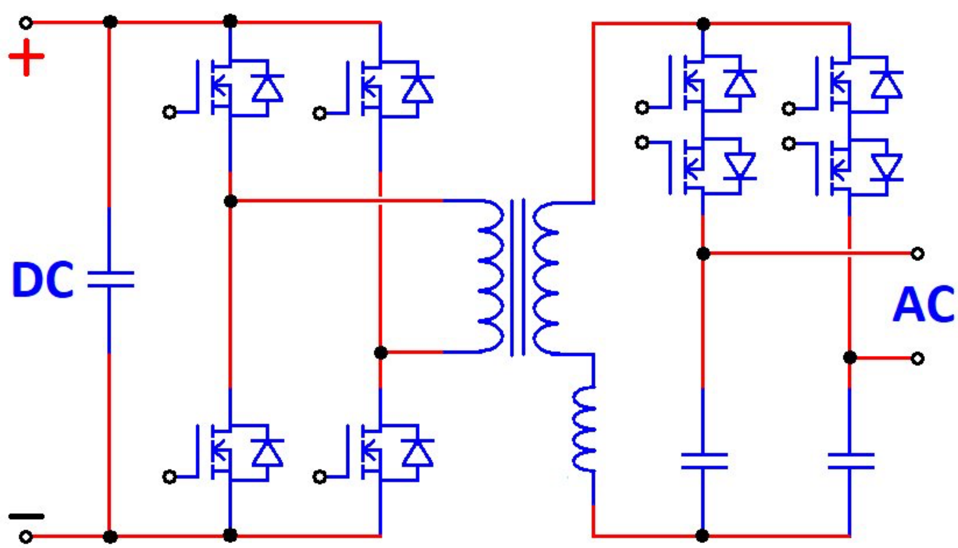
The Evolution of GaN BDS Technology

Enphase's decision to adopt GaN in the form of a Bi-Directional Switch (BDS) device traces back to 2011, coinciding with the market release of its third-generation M215 PV Microinverter. Although development of the fourth-generation M250 was already well underway, engineering leadership recognized it would be the final product built on Enphase's original "dual-interleaved flyback" circuit topology [1].

This pivot was driven by impending regulatory changes. Specifically, the California Public Utilities Commission (CPUC) was revising "Rule 21" - the landmark 1982 framework that facilitated distributed generation deployment - to mandate that "smart" PV inverters provide active power factor control by 2015 [2]. Mirroring this move, domestic and international utilities were drafting similar compliance mandates.

This regulatory evolution required Enphase to rethink its power conversion architecture: the dual-interleaved flyback topology was fundamentally incompatible with active power factor control. To meet these emerging requirements, Enphase had to abandon the architectural foundation of its first four product generations. The company required a new topology that could meet immediate power factor mandates while future-proofing devices against upcoming Advanced Grid Functions (AGF) then being debated across the utility sector.

After evaluating several candidates capable of supporting the full suite of smart AGF features, Enphase engineers selected a new architecture: a single-stage, dual-active-bridge, series-resonant cycloconverter.



A single-stage, dual-active-bridge, series-resonant, cycloconverter.

While the selection process weighed numerous variables, a decisive factor was that cycloconverter topologies inherently rely on BDS devices. Enphase engineers recognized a unique, lesser-known attribute of GaN HEMT technology, which had reached commercial maturity just two years prior in 2009 [3]. They realized that lateral GaN technology could be leveraged to develop a monolithically integrated GaN HEMT Bi-Directional Switch, laying the groundwork for Enphase's next era of power electronics.

Enphase's transition to this single-stage, dual-active-bridge, series-resonant, cycloconverter topology represents a major milestone in microinverter engineering. This shift allowed the company to meet evolving utility requirements while pioneering the use of Gallium Nitride (GaN) Bi-Directional Switches (BDS).

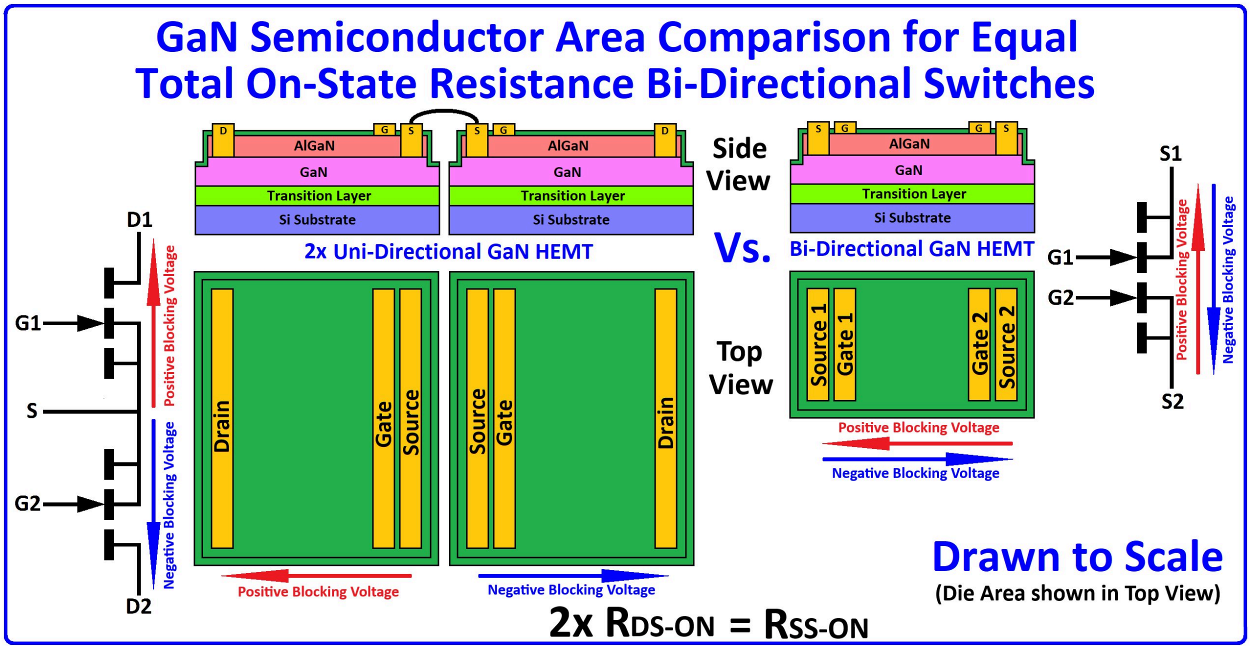
The Latent Value of GaN BDS Technology

Unlike conventional semiconductor power transistors that rely on vertical architectures, the GaN HEMT features a unique lateral structure. This unique structural difference enables the development of a monolithically integrated GaN HEMT BDS device.

Understanding this unique structural attribute highlights the latent value and disruptive potential of GaN HEMT technology. Cycloconverters represent one of the oldest classes of switched-mode power converters, first described in 1923 by engineer Louis A. Hazeltine in General Electric patent US-1,904,455. While the mechanics of cycloconverters are well understood, their commercial adoption has been hampered by prohibitive manufacturing costs and inherent complexity. Historically, the absence of native BDS devices forced engineers to construct composite bi-directional switches by connecting conventional, uni-directional transistors in an anti-series, back-to-back configuration. Consequently, cycloconverter topologies have been confined to massive industrial applications - such as wind turbines and large industrial variable-speed motor drives - where massive scale can justify the high cost of implementation.

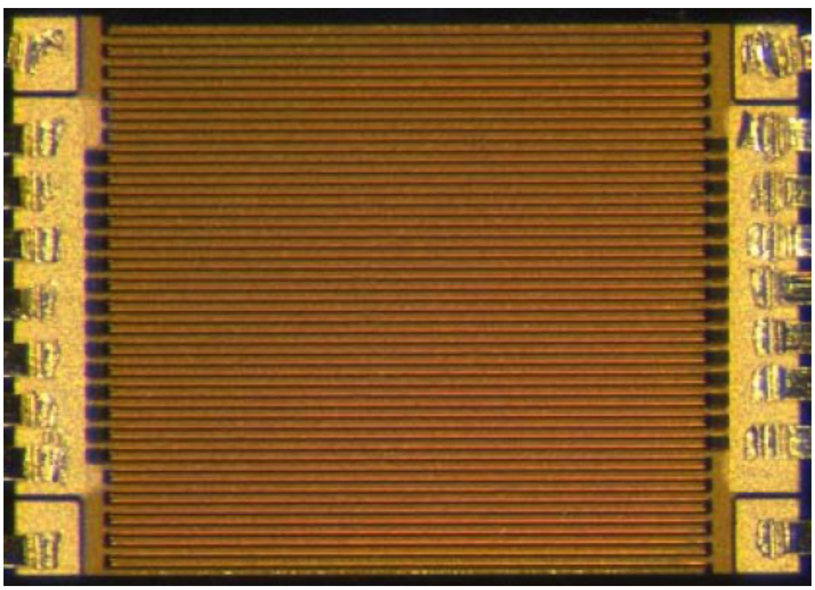
Enphase engineers recognized that a monolithically integrated GaN HEMT BDS device could turn a long-standing topology challenge into a practical product advantage. Native GaN BDS devices materially simplify cycloconverter topologies, making them far more cost-effective than standard dual-stage alternatives [4].

This paradigm shift in cost-efficiency stems directly from the GaN HEMT BDS architectural advantage. In a traditional composite bi-directional switch made of two back-to-back uni-directional devices, only one transistor blocks the applied voltage at any given time. Conversely, a single GaN BDS utilizes its solitary drift region to block a voltage of either applied polarity.



A 'cartoon' drawing illustrating the GaN HEMT structure and the inherent 4x die area advantage of the GaN HEMT BDS compared to an anti-series connected pair of back-to-back conventional uni-directional GaN HEMT devices.

Furthermore, because traditional back-to-back configurations place two devices in series, each uni-directional transistor must be physically upsized to counteract the doubled conduction losses. A single GaN BDS replaces both oversized components. Because it eliminates the need for two series connected devices that are each twice its size, the GaN BDS structure delivers a 4x die-area advantage over conventional back-to-back pairs [5]. This 4x reduction in semiconductor die footprint area translates directly into up to a 4x cost advantage, forming the foundational value proposition of GaN BDS technology.

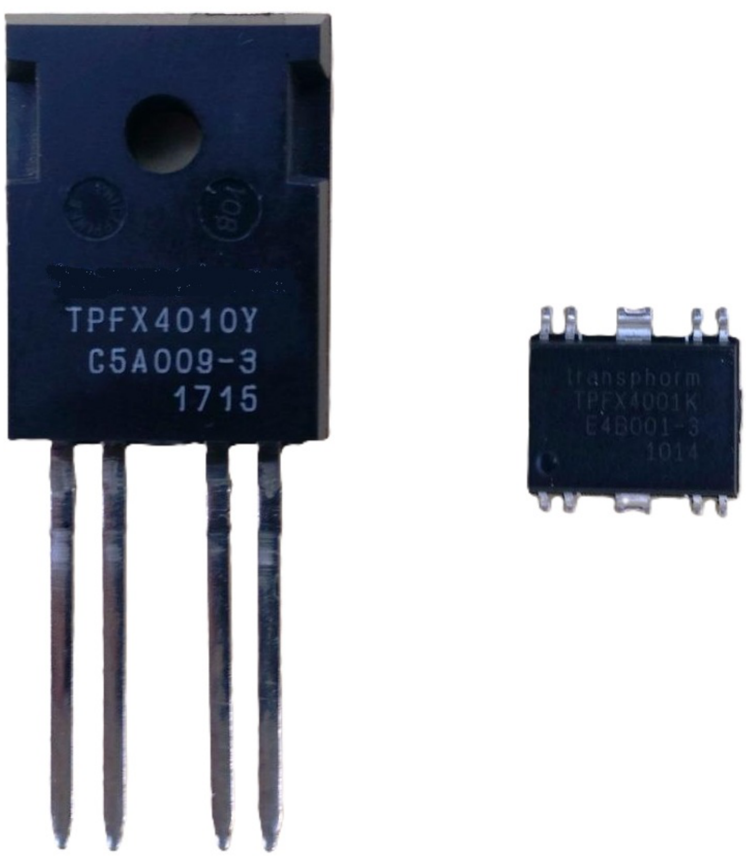


A closeup view of a GaN HEMT BDS device die [6].

02 GaN BDS Research & Development

The first experimental prototypes of monolithically integrated GaN BDS devices were developed in 2007 by a research team at Panasonic [7]. While the precise performance metrics of these early prototypes remain unclear, the research successfully demonstrated that GaN HEMT technology could support monolithic BDS integration. Crucially, this work signaled the inherent value of such devices to the broader power semiconductor industry. This foundational Panasonic technology was later advanced by Infineon under strategic joint development agreements formed in 2015 and 2021 [8, 9].

Concurrently, commercial partnerships accelerated Western development. In 2012, Enphase Energy collaborated with Transphorm - a US-based GaN start-up later acquired by Renesas in 2024. Funded by an ARPA-E Solar ADEPT project grant, this collaboration culminated in the successful fabrication of a functional, monolithically integrated GaN BDS prototype in 2013 [10].



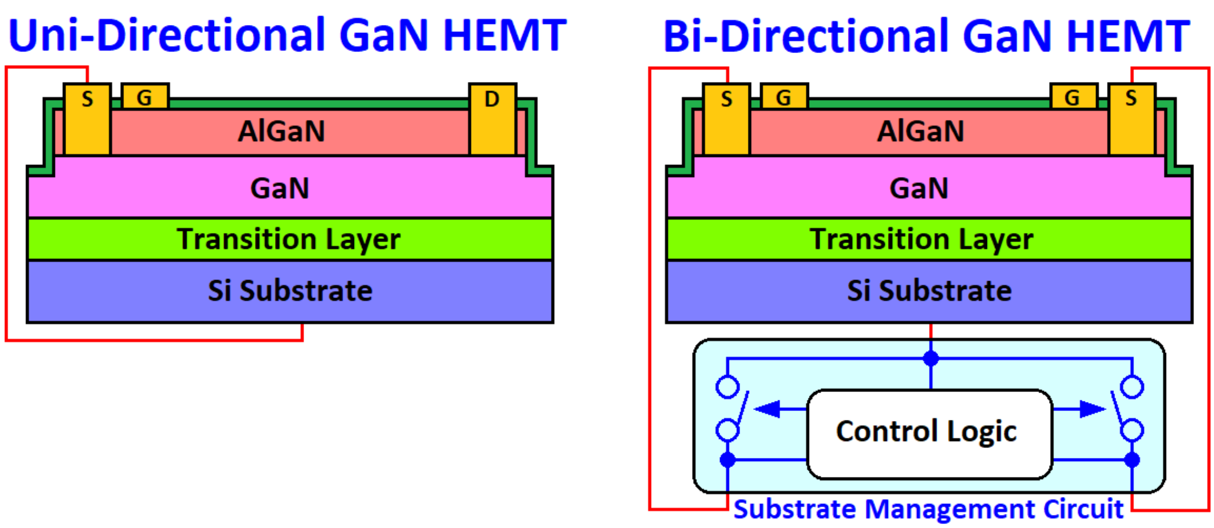
Prototype monolithically integrated GaN BDS devices developed with research funding from an ARPA-E Solar ADEPT project in 2013 - LHS = TPFX4010Y, 1.2kV, 200mΩ, RHS = TPFX4001K, 600V, 200mΩ.

03 GaN BDS Substrate Management Circuit

The most critical technological challenge in developing a monolithically integrated GaN HEMT BDS device lies in designing a specialized substrate management circuit. The silicon substrate on which a GaN HEMT device is fabricated requires its potential to be biased to the HEMT source voltage. In conventional uni-directional GaN HEMTs, biasing the silicon substrate to the source voltage is simple. The substrate is directly connected to the source terminal.

However, a GaN HEMT BDS features two distinct source connections. This creates a more complex design challenge. The substrate must always be biased by virtue of an electrical connection to whichever source terminal has the lower voltage potential.

To solve this, the specialized substrate management circuit must continuously measure the voltage difference between both sources. It then dynamically connects the substrate to the appropriate terminal based on that measurement.

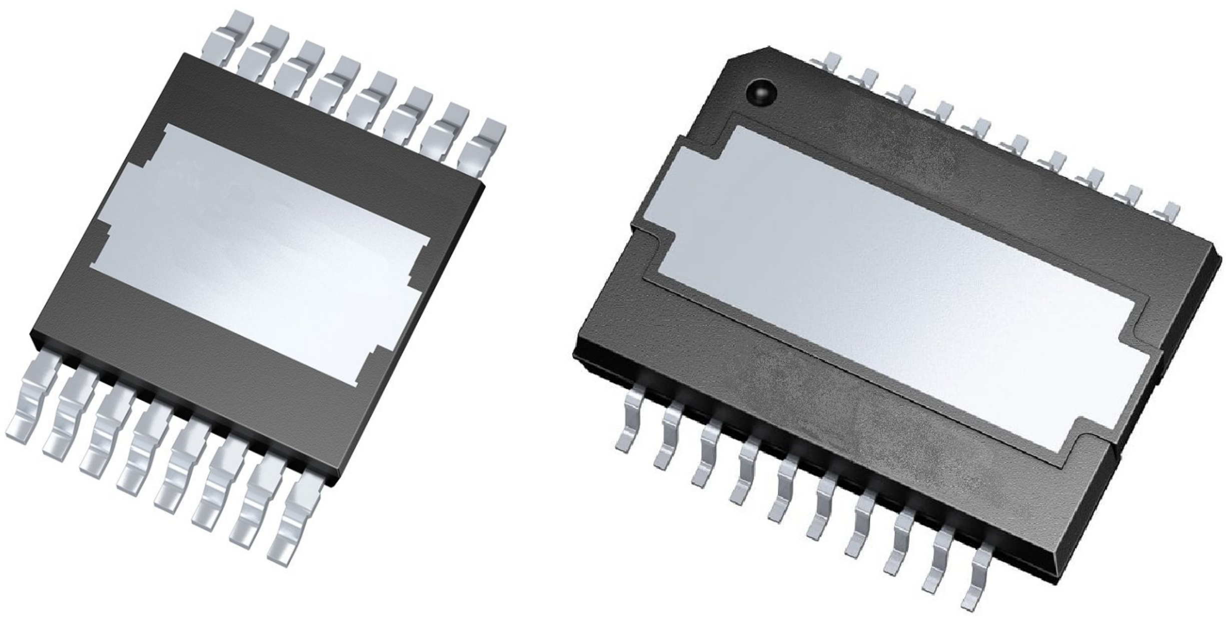


GaN HEMT BDS substrate management details.

Overall, GaN HEMT BDS device performance depends heavily on the accuracy and speed of this substrate management circuit [6]. It must respond rapidly to sudden voltage fluctuations – if the substrate is not connected to the correct terminal or fails to transition rapidly during a voltage polarity reversal, then the incorrectly biased silicon substrate acts like a “back-gate” which could unintentionally bias the device toward conduction. Integrating this circuit directly onto the GaN HEMT BDS die ensures optimal performance. It also abstracts the complexity away from power converter designers. They can then utilize the BDS without needing to design the underlying substrate management circuit.

04 Commercial Availability

Commercially available GaN HEMT Bi-Directional Switch (BDS) devices utilize industry-standard, top-side cooled surface-mount packages defined by the Joint Electron Device Engineering Council (JEDEC). This standardization allows multiple semiconductor companies to develop pin-for-pin compatible devices. This multi-supplier ecosystem can help Enphase reduce sourcing risk and support long-term platform scalability.



GaN HEMT BDS surface-mount top-side cooled packages: Left = TOLT (MO-332) & Right = DSO-20 (MO-166).

As of this writing, commercially available GaN BDS devices are offered by Infineon, Renesas, and Navitas. These initial components feature a 650V rated operational voltage and an 800V momentary surge voltage rating. They are available in industry-standardized maximum on-state resistance ($R_{SS\text{-}ON}$) values of 30mΩ, 70mΩ, and 140mΩ.

At the March 2026 Applied Power Electronics Conference (APEC) in San Antonio, Texas, STMicroelectronics and Texas Instruments announced and showcased their upcoming GaN HEMT BDS devices. These future offerings are expected to also conform to this existing industry GaN HEMT BDS standardization.

05 Performance Advantages of GaN BDS Technology

Although the GaN HEMT BDS structure represents a unique departure from traditional uni-directional GaN HEMT designs, it inherits all the performance and cost benefits of its predecessors on which the BDS structure is based, including enhanced efficiency, high frequency switching performance, and reliability, along with the cost advantages afforded by the BDS structure.

GaN HEMT Superior Transient Over-Voltage Robustness

Fundamentally, GaN HEMT technology offers superior over-voltage characteristics compared to incumbent Si MOSFETs. While traditional Si MOSFETs exhibit a "hard" avalanche characteristic for over-voltage protection, this mechanism is generally insufficient on its own, as the energy in a typical AC grid surge event is approximately a thousand times greater than what a Si MOSFET's avalanche capability can withstand.

The only practical solution to this surge energy robustness discrepancy is to design a dedicated surge energy clamp/filter circuit which employs a combination of surge suppression components: (inductors, capacitors, MOV, & TVS devices). In essence, the avalanche over-voltage clamping characteristic of conventional Si MOSFETs is simply too weak to provide any practical value.

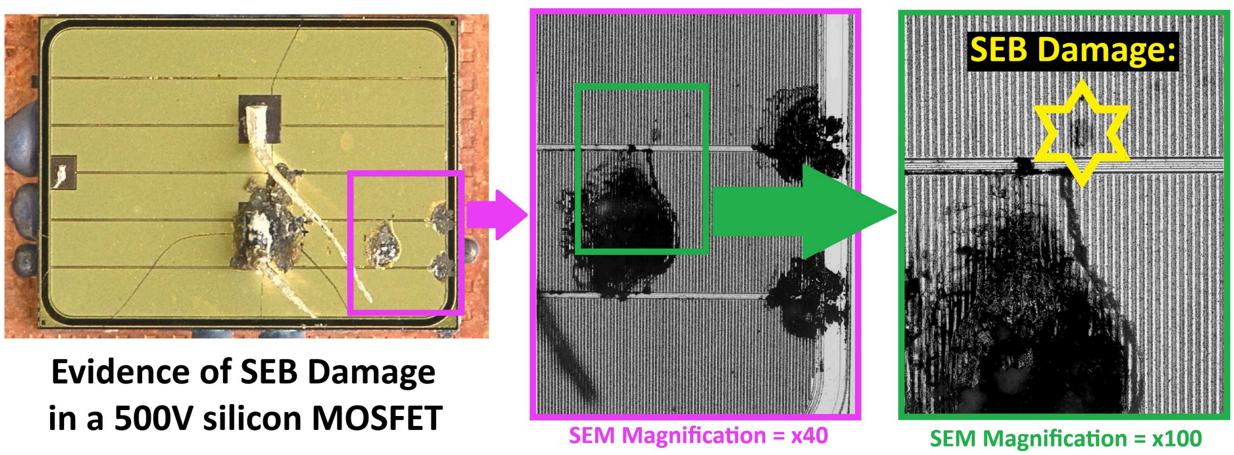
Conversely, GaN HEMT devices operate via "soft" and "hard" maximum voltage ratings rather than avalanche breakdown. A 650V GaN HEMT can tolerate transient over-voltage surges well above 800V, a feature that aligns better with AC grid transients. This robust surge capability allows for a less aggressive clamping circuit design, which significantly reduces wear-out in Metal Oxide Varistor (MOV) components [11]. By reducing MOV wear, the overall lifetime reliability and long-term surge robustness of the microinverter are substantially increased.

When 650V GaN HEMT devices first became commercially available back in 2009, there were concerns from the power electronics industry regarding the robustness of this technology in relation to AC grid voltage transient surge events, specifically due to GaN HEMT technology not exhibiting any over-voltage avalanche capability. The allowable over-voltage surge rating characteristic exhibited by GaN HEMT devices turns out to be much more extensible to providing a comprehensive, robust AC voltage surge solution than the conventional avalanche over-voltage characteristic of a silicon MOSFET.

GaN HEMT Superior SEB Robustness and Reliability

GaN HEMT devices are also fundamentally different from silicon MOSFET devices regarding the degree of susceptibility they have towards cosmic radiation. The radiation from the Sun creates heavy ions and secondary neutrons in the Earth's atmosphere. This cosmic radiation is responsible for creating Single Event Errors (SEE) in computer processors and memory. SEE is a computing inconvenience that is effectively mitigated using error correction techniques. In power transistors, the cosmic radiation that is responsible for SEE in computing applications goes by a different name, Single Event Burnout (SEB). SEB is far more than an inconvenience, as the name suggests the word 'burnout' refers to the fact that irreversible damage occurs which typically results in the destruction of the power transistor.

The first Si MOSFETs designed for use in AC grid connected power converters became commercially available in the mid-1970s. These first generation 'high-voltage' MOSFETs featured a voltage rating of 500V, which was initially considered to provide an adequate design safety margin for use in 240VAC grid connected converters. These first generation 500V Si MOSFETs proved to be far from reliable and in the mid-1990s several researchers made the connection that this low reliability was directly linked to SEB failures [12].



Evidence of Single Event Burnout damage in a 500V Si MOSFET.

In response to this research Si MOSFET manufacturers mitigated this inherent SEB vulnerability by increasing the voltage rating up to 600V in the early 2000s and then further increasing the voltage rating up to 650V in the late 2010s. These latest 650V rated Si MOSFETs are now considered to have adequate reliability regarding SEB vulnerability.

In contrast to the dubious reliability history related to SEB vulnerability with Si MOSFETs, the history for GaN HEMT devices has followed a different path. The high bandgap for GaN makes GaN HEMT devices particularly immune to SEB related failures, and this fact underpins one of the first applications that GaN HEMT technology was developed for. One of the first applications in which GaN HEMT devices were deployed was in communications satellites [13], a well understood and hostile environment for electronics due to the inherent exposure to high levels of cosmic radiation.

It is also worth noting the relative SEB robustness of SiC - the other competing wide-bandgap technology. SiC MOSFETs share significant architecture with their silicon predecessors, including an avalanche over-voltage capability. This specific feature led design engineers to adopt the same minimal over-voltage design margin strategy previously used for silicon MOSFETs. Consequently, this design choice inadvertently compromised the device's SEB robustness. When SiC MOSFETs first entered the commercial market in 2010, this vulnerability was masked when compared strictly to legacy silicon technology. However, any meaningful benchmark had to account for GaN HEMT technology, which launched commercially around the same time and demonstrated significantly stronger SEB resilience. To counter this performance gap, some industry participants emphasized GaN HEMT's inherent lack of avalanche over-voltage capability as a reliability concern – a characterization that, as the data above demonstrates, does not reflect the comparative SEB performance of the two technologies.

Multiple academic and industry studies support the relative SEB robustness advantage of GaN HEMT devices compared with Si and SiC MOSFET devices. One such whitepaper [14] includes this table below that shows that SEB robustness of GaN HEMT devices is of the order of 10x better than comparable SiC MOSFET devices and in the order of 60x better than comparable Si MOSFET devices.

type	sample	ratings	Vds stress (V)	FIT (CL60)	failure
Cascode GaN	TP65H035G4WS	650V 35mΩ	650	0.012	no failure(sample size=20)
Si MOSFET	Low voltage Si MOSFET for Cascode GaN	30V	30	0.027	no failure(sample size=10)
SiC MOSFET	SiC A	650V 120mΩ	650	0.041	1 out of 10 failed
	SiC B	650V 60mΩ	650	0.41	5 out of 8 failed
Si MOSFET	Si super junction	600V 180mΩ	600	7.6	5 out of 5 failed

Comparison of SEB robustness for GaN HEMT vs Si & SiC MOSFET devices [14].

While Enphase microinverters are not currently intended for aerospace applications, adopting GaN for its superior SEB robustness remains a critical terrestrial design consideration. The relationship between SEB susceptibility and long-term reliability is a matter of statistical probability. Although incumbent silicon MOSFET technology offers adequate reliability, GaN HEMT technology delivers the potential for improved long-term reliability. This advantage stems directly from its lower vulnerability to SEB and its inherent ability to tolerate higher electric fields.

GaN HEMT Superior Efficiency

The intrinsic properties of GaN as a semiconductor material are inherently better than those for silicon which has been used as the semiconductor material of choice for power transistors since the mid-1950s. The bandgap energy for GaN is over three times better than for Si; the breakdown electric field for GaN is eleven times better than for Si, while the electron mobility in GaN is 33% higher than for Si [15].

Combining all these superior semiconductor material properties together is the reason why GaN HEMT devices inherently perform better than conventional silicon MOSFET devices. A die area comparison between equivalent on-state resistance rated 650V GaN and Si transistors shows an approximate 3x advantage for the GaN HEMT compared to the Si MOSFET [16]. On top of this 3x factor, adding the 3x to 4x die area advantage afforded by the monolithically integrated GaN HEMT BDS structure results in a GaN HEMT BDS device having an approximate 10x die area advantage compared to an equivalent series connected back-to-back pair of silicon MOSFETs.

This reduction in size afforded by a GaN HEMT over an equivalent on-state resistance Si MOSFET results in the GaN HEMT requiring a much lower gate charge to be applied to turn the device on. In addition, the HEMT architecture uses a thicker wide-bandgap barrier than the MOSFET insulator, resulting in lower gate capacitance per unit gate area. A direct comparison of the gate charge required for a GaN HEMT vs a Si MOSFET device reveals a factor of 10x advantage in favor of the GaN HEMT UDS device (assuming equivalent on-state resistance GaN HEMT vs Si MOSFET devices). Repeating this comparison for the monolithically integrated GaN HEMT BDS and the alternative series connected back-to-back pair of Si MOSFETs increases the gate charge advantage to a factor of 20x in favor of the GaN HEMT BDS device.

The fact that a GaN HEMT BDS can be turned on with a much lower applied gate charge directly translates into GaN HEMT BDS devices being able to achieve higher power conversion efficiency than their equivalent Si MOSFET counterparts.

This lower gate charge and lower gate voltage also translates into the ability of GaN HEMT BDS devices to support a much higher switching frequency than their silicon MOSFET counterparts without incurring unacceptably high gate drive power losses. This higher switching frequency can be leveraged to shrink the magnetics and other passive filter components in the microinverter for additional cost and power loss savings.

GaN HEMT Superior Performance

Introduced in December 2025, Enphase’s new IQ9 Series Microinverters for PV are designed for commercial and industrial solar applications. The superior performance afforded by GaN HEMT BDS technology is the key enabler behind these new C&I focused microinverters.

By leveraging the increased over-voltage surge rating of GaN HEMT BDS, the microinverter’s operating voltage extends up to 277VAC. This allows for operation in 480VAC three-phase commercial systems, the standard C&I voltage in the United States.

To accommodate the high-power PV modules common in the C&I sector, the IQ9 Series offers output power ratings of 427W and 548W, supporting PV modules that exceed 700W. Furthermore, the exceptional efficiency of GaN HEMT BDS enables Enphase to deliver higher power density without a proportional increase in physical size or cost.

Enphase IQ9S-3P Microinverter for PV (548W).

The IQ9 Series Microinverters demonstrate how GaN BDS technology can expand Enphase's microinverter platform into higher-power commercial applications.

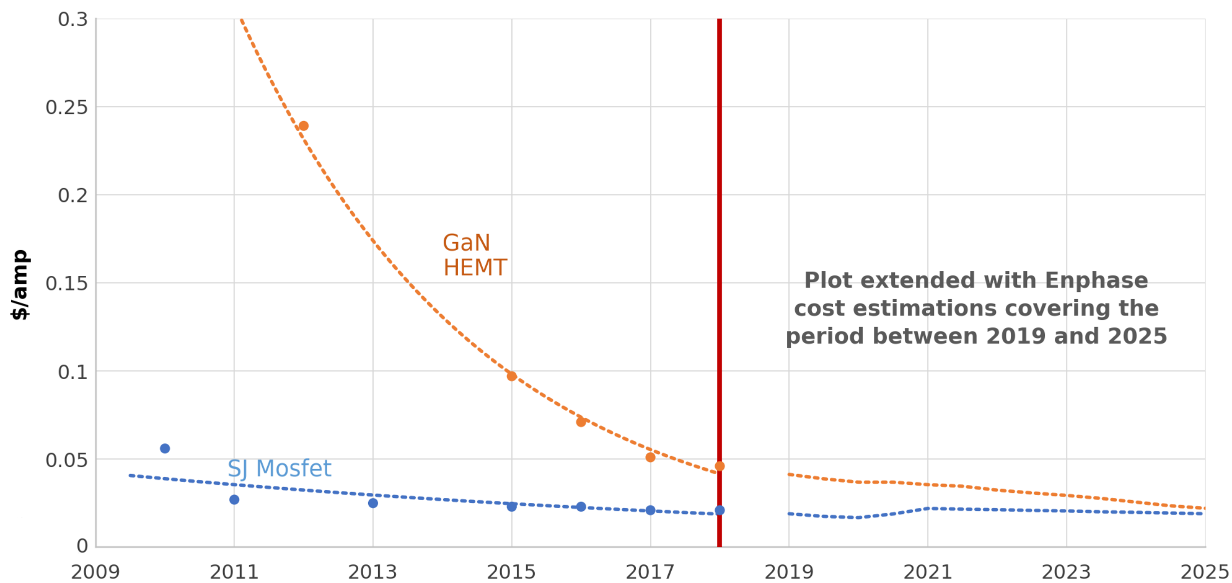
06 GaN HEMT BDS Cost Advantage

GaN HEMT is a relatively new technology. Conventional GaN HEMT uni-directional devices are still currently commanding higher prices than silicon (Si) MOSFETs with equivalent voltage and on-state resistance ratings.

Recognizing the power semiconductor market dynamics, Enphase realized that a monolithically integrated GaN HEMT BDS offers a potential 4x die area and cost advantage over a series-connected, back-to-back conventional BDS solution. This architectural integration provides an important architectural advantage, making a single GaN HEMT BDS more cost-effective than two conventional uni-directional GaN HEMTs, and even more cost-effective than an equivalent back-to-back Si MOSFET configuration.

Had Enphase simply adopted conventional uni-directional GaN HEMT devices, the company would have paid a premium over its existing silicon-based architecture. Instead, transitioning to GaN HEMT BDS technology supports cost reduction compared to the incumbent Si MOSFET solutions utilized in its IQ7 and IQ8 Series Microinverters.

The relative maturity of GaN HEMT versus Si MOSFET technology is the primary driver of their future cost trajectories. Silicon power transistor technology is highly mature, benefiting from over 50 years of commercial and manufacturing refinements that have largely plateaued its pricing. In contrast, conventional GaN HEMT UDS devices have been commercially viable for only 15 years, and commercial GaN BDS technology remains early in its cost-reduction curve. Historical data demonstrates significant price erosion for standard GaN HEMT UDS devices [17], and a similar downward cost trajectory is expected as volumes increase, and manufacturing matures for GaN HEMT BDS technology over the next few years.



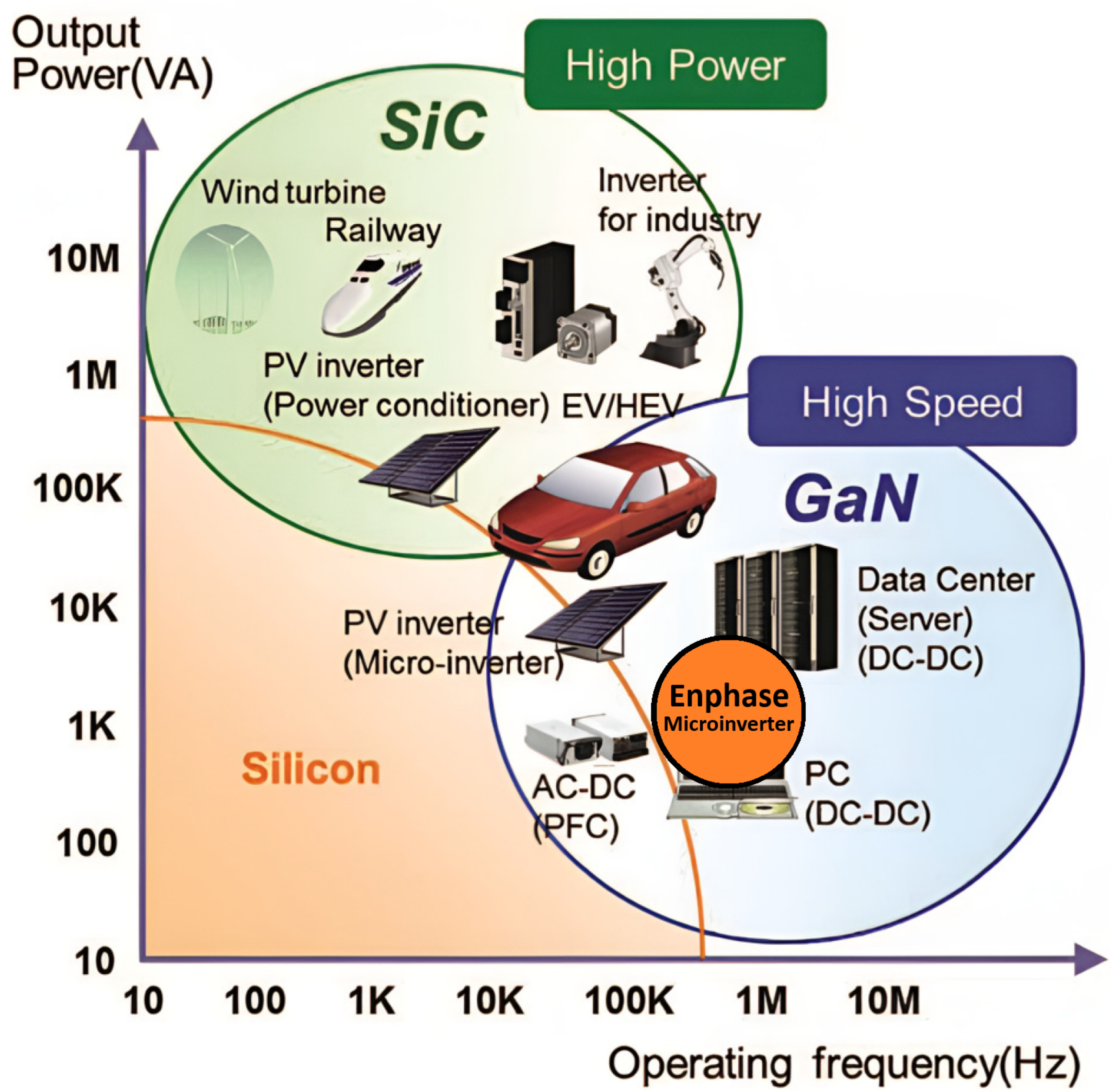
GaN HEMT vs Si MOSFET cost evolution 2010, 2018 [17] - Extended with Enphase estimated cost data for the period between 2019 and 2025.

07 GaN Versus SiC: Complementary Technologies

Gallium Nitride (GaN) and Silicon Carbide (SiC) are often discussed together, but they are best understood as complementary technologies competing for WBG market dominance. These complementary technologies possess unique material strengths tailored to distinct power conversion applications. As noted in the introduction, SiC is well suited for high-power traction, grid, and industrial applications, while GaN is attractive where high frequency, compact magnetics, and modular lower-to-medium power conversion are important.

This application split between SiC and GaN technology stems fundamentally from the WBG semiconductor material and structural property differences. In essence, SiC MOSFET devices scale up to higher power ratings but become economically impractical at lower power levels. Conversely, GaN HEMT technology is very suitable for making low power devices but does not yet economically scale up to ultra-high-power semiconductor devices. Furthermore, GaN maintains a high-frequency advantage over both Si and SiC MOSFETs that have high gate capacitance due to the vertical device structure and require higher gate voltages for full turn-on. Enphase power converters leverage GaN devices' superior high-frequency capabilities to achieve compact transformer sizes and higher overall efficiencies. Additionally, vertical SiC MOSFET devices offer no semiconductor die area advantages for BDS topologies, unlike lateral GaN.

Industry observers often question why Enphase's architecture aligns naturally with the GaN operating range. This bias is driven by WBG manufacturing economics and material physics rather than engineering bias on Enphase's part. The power ratings of Enphase's modular microinverter circuit topology align perfectly with the economic "sweet spot" for GaN HEMT technology. In contrast, these power levels remain less attractive from a cost-performance standpoint for SiC MOSFET devices.



This power conversion application space plot shows the semiconductor 'sweet spots' for Si, SiC, and GaN transistors [18]. The range of operating frequency and output power for all Enphase microinverter products has been added (in scale) to this plot.

08 Industry Milestone: PCIM 2025 Announcement

PCIM (Power Conversion, Intelligent Motion) is a prominent international exhibition that is held annually in three different locations: Nuremberg Germany, Shanghai China, and New Delhi India. This conference focuses on:

- Power electronics
- Intelligent motion (i.e., motor drives)
- Renewable energy
- Energy management

The PCIM conference held in Nuremberg Germany in May 2025 served as the venue for the public announcement regarding the commercial availability of GaN BDS devices by the three semiconductor companies: Infineon, Navitas, and Renesas. This conference was attended by approximately 16,500 industry visitors.

This GaN BDS public announcement was delivered in the format of the second day keynote speech delivered by Enphase Energy's Senior Power Electronics Architect, Michael Harrison. This presentation, along with a more detailed accompanying technical whitepaper called: "Monolithically Integrated GaN HEMT Bi-Directional Switch (BDS)" is available [19].

The May 2025 public announcement regarding the commercial availability of GaN BDS devices from Infineon, Navitas, and Renesas. Delivered as a keynote speech and accompanying presentation at the PCIM conference in Nuremberg, Germany.

09 The Future of GaN Across the Enphase Platform

The adoption of GaN HEMT technology at Enphase began with the introduction of GaN BDS devices in the IQ9 Series Microinverters for PV applications. This same GaN HEMT BDS technology will also be featured in the upcoming IQ10® generation of multi-phase microinverters. These upcoming microinverters are expected to support Enphase's fifth-generation energy storage batteries, bi-directional EV chargers, and the IQ SST product announced on April 28, 2026 [20]. Within the IQ9 and IQ10 Microinverter architectures, GaN HEMT BDS technology is used exclusively in the high-voltage AC bridges, while high-voltage GaN HEMT Uni-Directional Switch (UDS) technology is utilized exclusively in any high-voltage DC bridges. Conversely, any low-voltage DC bridges currently retain silicon (Si) MOSFET power transistors.

Both Si MOSFETs and GaN HEMTs are bifurcated into high-voltage (>600V) and low-voltage (<200V) classes. This division is driven by industry application requirements and distinct technological trajectories. While high-voltage GaN HEMT technology (both UDS & BDS) has reached commercial maturity – almost achieving cost parity with incumbent Si MOSFETs - low-voltage GaN technology temporarily lags due to the exceptional performance-to-cost ratio of established low-voltage Si MOSFETs. However, low-voltage GaN HEMT devices are projected to surpass Si equivalents in cost-effectiveness in the near future. This anticipated market shift drives Enphase's advanced engineering research initiative, which focuses on developing a next-generation microinverter design that adopts low-voltage GaN HEMT devices for the DC bridge.

Future Enphase microinverter architectures are expected to increasingly move toward 'all GaN' designs employing GaN HEMT UDS devices in the DC bridge and GaN HEMT BDS devices in the AC bridge. This 'All GaN' design strategy is expected to enable considerably higher switching frequency to be employed, which enables a reduction in the size of the microinverter magnetics and other passive filter components. This allows for further improvements in the microinverter power rating while also resulting in significant cost reductions.

Published technical literature suggests that the voltage rating for GaN HEMT technology is capable of being extended up to 1.2kV [21 & 22]. Enphase is working with semiconductor partners on the development path for higher-voltage GaN BDS technology, including potential 1.2kV-class devices that are positioned to enable a native three-phase microinverter allowing for 480VAC delta connection, providing increased power rating with anticipated additional system level cost savings.

10 GaN BDS and the Enphase IQ SST Architecture

On the 28th of April 2026, Enphase announced the development of their IQ® Solid-State Transformer (IQ® SST) for use in AI data center applications [23]. This IQ SST is targeted at meeting the 800VDC (±400VDC) power delivery needs for the next generation of AI data centers which are highly dynamic, resulting in load fluctuations between 10% and 100% several times per second [24].

Enphase engineers recognized that the existing IQ Microinverter platform would make the ideal building block for use in a modular SST product designed to serve the dynamic power requirements in AI data centers.

The small power rating of Enphase IQ Microinverters relies on the use of small circuit inductance values operated at high switching frequency, resulting in exceptionally fast control response time. This fast control response is positioned to enable the effective fast transmission of AI load changes to large scale Battery Energy Storage Systems (BESS) located outside the data center in the black-space area, potentially eliminating the need to locate Battery Backup Units (BBU) and Uninterruptible Power Supply (UPS) units in the space-constrained data center white-space and gray-space areas.

The Enphase IQ SST 4kW power module is based on the existing IQ10 Microinverter with variants that have been developed for use in the 5th generation energy storage battery product as well as the planned DC-connected bi-directional EV charger.

This design reuse of the IQ10 Microinverter to form the basis of the IQ SST power module is designed to allow Enphase to leverage the existing supply chain based on high volume commodity components, with existing manufacturing facilities and proven high quality manufacturing processes.

This distributed modular architectural approach being adopted by Enphase for the IQ SST power module results in the IQ SST using a much higher number of lower-powered modules than those used by many competitors.

The 4kW IQ SST power module is designed to support an Input-Series, Output-Parallel (ISOP) modular SST with a total of 342 individual power modules being connected as three strings of 114 modules connected in a delta configuration to a Medium Voltage (MV) 34.5kV utility grid supply. This design provisions a 10% redundancy that allows as few as 103 power modules per string to meet all performance specifications. Accordingly, each power module will operate from a nominal AC input voltage range from 303VAC to 335VAC RMS, with additional operational margin to cover AC grid voltage regulation as well as expected operational transient under-voltage and over-voltage conditions.

This 335VAC RMS operational requirement is 40% higher than the standard single-phase 240VAC RMS voltage level than can be reliably serviced using 650V rated power semiconductor switches. Accordingly, the IQ SST power module will make use of a new voltage class of 900V rated GaN BDS devices. This ~40% increase in the GaN BDS rated voltage matches the 40% increase in the IQ SST power module AC operational voltage.

The existing commercially available 650V rated GaN BDS devices that feature an 800V momentary surge voltage rating are fabricated using a GaN on silicon process. By increasing both the lateral and vertical GaN HEMT feature dimensions, it is possible to extend these GaN BDS designs to support a rated operational voltage of 900V, with a momentary surge voltage rating of 1.1kV. This is currently believed to be the practical economic limit for the existing GaN-on-silicon process, with development of 1.2kV GaN BDS devices being based on GaN on some form of insulative substrate such as sapphire (Al2O3) or the engineered Qromis Substrate Technology (QST) [25].

Several semiconductor companies are currently developing 900V rated variants of GaN BDS devices based on existing GaN on silicon processes. These 900V rated variants are targeted for adoption in Electric Vehicle (EV) On Board Charger (OBC) applications enabling compatibility for operation from a three-phase utility grid (380VAC to 480VAC RMS). This intended application results in devices with a maximum on-state resistance of 15mΩ being developed which are ideally sized for use in the Enphase 4kW IQ SST power module. Engineering samples of these 900V rated GaN BDS devices are currently being evaluated in the Enphase IQ SST power module and fully JEDEC-qualified production parts are expected to be available by the end of 2026.

The IQ SST power module is designed to support both the NVIDIA 800VDC as well as the Open Compute Project (OCP) ±400VDC requirements. The DC output will be produced using a series connected pair of 400VDC bridges. Each of these output bridges will make use of 650V rated GaN HEMT Uni-Directional Switch (UDS) devices. This converter topology choice using a series connected pair of DC bridges is designed to support the OCP split-rail ±400VDC configuration and provide a practical path toward future higher-voltage DC architectures such as 1,500VDC based on a ±750VDC design that is expected to use 900V GaN UDS devices.

To maximize design efficiency, semiconductor manufacturers are currently co-developing 900V GaN UDS and BDS devices using a unified platform architecture. This common design framework features limited variation between the two device derivatives, enabling expected shared development resources. Consequently, both the bi-directional and uni-directional variants can undergo parallel design and qualification.

11 Conclusion

Enphase's adoption of GaN bidirectional switch technology marks an important step in the evolution of its power conversion platform. GaN BDS devices enable compact, efficient, high-frequency bi-directional power conversion, making them well suited for the next generation of Enphase products across solar, storage, EV charging, and AI data center infrastructure.

The significance of this technology extends beyond a single device substitution. By combining GaN BDS devices with Enphase's modular architecture, embedded control, and high-volume manufacturing platform, Enphase is building a scalable foundation for higher-power, higher-density, and more flexible power conversion systems.

In commercial solar, GaN BDS technology enables higher AC voltage operation and supports Enphase's expansion into 480V three-phase applications. In storage and bi-directional EV charging, it supports controlled bi-directional energy flow across the home, vehicle, and grid. In AI data centers, the same technology foundation is being extended into the IQ SST architecture, which is designed to deliver 800V DC power using a distributed, modular conversion platform.

As GaN device technology continues to mature, Enphase expects further improvements in cost, efficiency, switching frequency, and power density. This creates a path toward increasingly integrated GaN-based power platforms that can serve a broader range of applications while preserving the reliability, manufacturability, and modularity that define the Enphase system architecture.

12 References

[1] Fornage, Martin. 2014 "Method and Apparatus for Converting Direct Current to Alternating Current." US Patent 8,717,780 filed September 13, 2010, and issued May 6, 2014.

[2] J. Ormond, "California's Interconnection Rule 21 Smart Inverter & the Smart Inverter Working Group," California Public Utilities Commission, 2014. https://share.google/cB2MyR5JNYOref2Je

[3] "Fujitsu Develops World's First Gallium-Nitride HEMT for Power Supply." https://www.fujitsu.com/global/about/resources/news/press-releases/2009/0624-01.html

[4] J. Kolar, et al. "Monolithic Bi-Directional Switches, Opening New Horizons in Power Electronics." International Conference on Silicon Carbide and Related Materials ICSCRM 2022.

[5] F. Vollmaier et al., "Performance Evaluation of Future T-Type PFC Rectifier and Inverter Systems with Monolithic Bidirectional 600 V GaN Switches," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), Vancouver, BC, Canada, 2021, pp. 5297-5304, doi: 10.1109/ECCE47101.2021.9595422.

[6] C. Kuring et al., "Impact of Substrate Termination on Dynamic On-State Characteristics of a Normally-off Monolithically Integrated Bidirectional GaN HEMT," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 2019, pp. 824-831, doi: 10.1109/ECCE.2019.8912793.

[7] T. Morita et al., "650 V 3.1 mΩcm² GaN-based monolithic bidirectional switch using normally-off gate injection transistor," 2007 IEEE International Electron Devices Meeting, Washington, DC, USA. pp. 865-868, doi: 10.1109/IEDM.2007.4419086.

[8] "Infineon and Panasonic Will Establish Dual Sourcing for Normally-Off 600V GaN Power Devices." 2015.https://powerelectronicsmagazine.net/article/96561/Infineon_and_Panasonic_Will_Establish_Dual_Sourcing_for_Normally-Off_600V_GaN_Power_Devices

[9] "Infineon and Panasonic accelerate GaN technology development for 650 V GaN power devices." 2021. https://www.gsma.com/get-involved/gsma-membership/gsma_resources/infineon-and-panasonic-accelerate-gan-technology-development-for-650-v-gan-power-devices/

[10] ARPA-E Advanced Research Projects Agency, Energy, Solar ADEPT Program, "Efficient Switches for Solar Power Conversion," 2012. https://arpa-e.energy.gov/programs-and-initiatives/search-all-projects/efficient-switches-solar-power-conversion

[11] I. Vernica et al., "Loss and Thermal Modeling of Metal Oxide Varistors (MOV) Under Standard Current Surge Mission Profile," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 2019, pp. 7113-7117, doi: 10.1109/ECCE.2019.8913287.

[12] E. Normand et al., "Neutron-induced single event burnout in high voltage electronics," in IEEE Transactions on Nuclear Science, vol. 44, no. 6, pp. 2358-2366, Dec. 1997, doi: 10.1109/23.659062.

[13] "Demonstrating the capability of GaN HEMTs for satellite communication," 2016. https://compoundsemiconductor.net/article/99943/Demonstrating_the_capability_of_GaN_HEMTs_for_satellite_communication

[14] K. Shono, Y. Kotani, R. Barr, L. Shen and S. Wienecke, "Cascode GaN Power Transistor Robust for Single Event Burnout Caused by Neutron Irradiation," 2025 IEEE International Reliability Physics Symposium (IRPS), Monterey, CA, USA, 2025, pp. 1-4, doi: 10.1109/IRPS48204.2025.10983763.

[15] M. Fatahilah et al., "3D GaN nanoarchitecture for field-effect transistors." 2019. Micro and Nano Engineering. 3. 10.1016/j.mne.2019.04.001.

[16] G. Deboy, "The Road to Success for Power," 2019. https://www.powersystemsdesign.com/articles/the-road-to-success-for-power-semiconductors/22/15065

[17] "GaN-on-Si HEMT vs SJ MOSFET: Technology and Cost Comparison report," 2016. https://www.yolegroup.com/technology-outlook/transphorming-the-power-transistor-industry-using-gan/

[18] T. Ueda, "Reliability issues in GaN and SiC power devices," *2014 IEEE International Reliability Physics Symposium*, Waikoloa, HI, USA, 2014, pp. 3D.4.1-3D.4.6, doi: 10.1109/IRPS.2014.6860629.

[19] M. Harrison, "Monolithically Integrated GaN HEMT Bi-Directional Switch (BDS)," PCIM Conference 2025, International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nürnberg, Germany.

[20] Enphase Energy Announces Development of IQ Solid-State Transformer for AI Data Centers. April 28, 2026. https://investor.enphase.com/news-releases/news-release-details/enphase-energy-announces-development-iq-solid-state-transformer

[21] S. Kumar et al., "1.2 kV Enhancement-Mode p-GaN Gate HEMTs on 200 mm Engineered Substrates," in IEEE Electron Device Letters, vol. 45, no. 4, pp. 657-660, April 2024, doi: 10.1109/LED.2024.3361164.

[22] M. Basler et al., "Highly-Integrated 1200 V GaN-Based Monolithic Bidirectional Switch," PCIM Conference 2025; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nürnberg, Germany, pp. 705-710, doi: 10.30420/566541089.

[23] Enphase Energy Publishes Technical White Paper on IQ SST Architecture for AI Data Centers. May 04, 2026. https://enphase.com/download/iq-sst-white-paper

[24] NVIDIA Technical Blog, "How New GB300 NVL72 Features Provide Steady Power for AI," Figure 1. July 28, 2025. https://developer.nvidia.com/blog/how-new-gb300-nvl72-features-provide-steady-power-for-ai/

[25] Qromis Substrate Technology (QST). http://www.qromis.com

Enphase Adoption of GaN Bi-Directional Switch Technology for Distributed Power Electronics

Enphase Energy, Inc.
47281 Bayside Parkway, Fremont, CA 94538
enphase.com